

# Observing Higgs Dark Matter at the CERN LHC

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Triggering the electroweak symmetry breaking may not be the only key role played by the Higgs boson in particle physics. In a recently proposed warped five-dimensional  $SO(5) \otimes U(1)$  gauge-Higgs unification model the Higgs boson can also constitute the dark matter that permeates the universe. The stability of the Higgs boson in this model is guaranteed in all orders of perturbation theory by the conservation of an *H-parity* quantum number that forbids triple couplings to all SM particles. Recent astrophysical data constrain the mass of such a Higgs dark matter particle to a narrow window of 70–90 GeV range. We show that the Large Hadron Collider can observe these Higgs bosons in the weak boson fusion channel with about  $240 \text{ fb}^{-1}$  of integrated luminosity in that mass range.

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## A. Introduction

The mechanism responsible for the breaking of the electroweak symmetry from  $SU(2)_L \otimes U(1)_Y$  to  $U(1)_{em}$  and the necessity of existence of cold dark matter (CDM) relics in the universe have motivated a large theoretical effort towards a beyond Standard Model (SM) physics in the last decades.

The electroweak symmetry breaking (EWSB) [2, 3] is achieved in the Standard Model (SM) and in many of its extensions introducing scalars whose couplings to fermions and gauge bosons generate their masses. Within SM there remains a scalar particle in the spectrum: the Higgs boson. One of the major goals of the LHC is the detection and the study of the properties of the Higgs boson which, in this respect, constitutes a window for the whole EWSB mechanism and hopefully for the high energy structure of the new physics. On the other hand, the indirect detection of the dark matter particle at colliders (whose existence has been established by the WMAP experiment [1]) is important to establish the nature of dark matter and, again, constitute a mean to decide between new physics models.

In a recent work [4] an interesting connection between these two phenomena was proposed: the Higgs boson could also be the dark matter relic with a mass of 70 GeV in order to satisfy the constraints from WMAP [1]. This connection has a deep impact in the Higgs boson phenomenology at colliders because the Higgs boson becomes absolutely stable in this warped 5D  $SO(5) \otimes U(1)$  gauge-Higgs model. As a consequence of the conservation of a new quantum number which forbids all triple couplings to SM particles leaving only the quartic couplings to bosons and fermions the Higgs boson acquires a property shared by *R-parity* conserving particles of the Minimal Supersymmetric Standard Model (MSSM) [5] and *KK-parity* conserving particles from Universal Extra Dimensions (UED) [6] scenarios for example – they are produced at colliders exclusively in pairs.

In Ref. [7] the double Higgsstrahlung channel  $pp \rightarrow (W, Z)HH$  was considered at the LHC as a possible detection channel but the backgrounds were found to be three orders of magnitude larger than the signal which would demand an extremely large amount of data for detection. Top quark and weak boson pair production can receive contributions from quartic Higgs boson couplings but at one-loop level. Moreover, these kinds of processes must be initiated by bottom partons once Higgs couples to mass. Associated production of Higgs and top or bottom quark is possible though  $f\bar{f}HH$  is a dimension-five operator suppressed by a factor  $m_f/v^2$  where  $v = 246 \text{ GeV}$  is the Higgs vev.

In Ref. [9] the potential of the LHC to discover Higgs bosons with SM couplings to weak bosons decaying into invisible particles like gravitons, gravitinos or neutralinos is demonstrated in the weak boson fusion (WBF) channel  $pp \rightarrow jjH \rightarrow jjE_T$ . In this case the far forward tagging jets work as an experimental trigger at the same time they endow the signal events singular features that make the separation from background events possible. The discovery potential of the LHC in the WBF channel has been established for a number of SM Higgs boson decaying channels [10], Higgs bosons of the MSSM [11], and in other models [12].

Being electrically neutral, weakly interacting, and absolutely stable the detectors would miss all Higgs signals – only indirect detection would be possible via large missing momentum topologies, a typical dark matter signal at

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colliders. Such signals need additional charged leptons or jets which can serve as an experimental trigger just like the invisibly decaying Higgs case of Ref. [9]. We thus propose the weak boson fusion

$$pp \rightarrow jjHH \rightarrow jj\cancel{E}_T \quad (1)$$

as a potential searching channel at the LHC. The two far forward tagging jets working as the required trigger plus the large amount of missing momentum associated to the stable Higgses constitute our signal. Moreover, contrary the SM case [3, 13], cancellations among triple and quartic Higgs contributions do not take place which results in a sizable production cross section as we discuss in section B.

Resuming in this work we investigate the Higgs pair production of the gauge-Higgs unification model proposed in Ref. [4] in the weak boson fusion channel at the 14 TeV LHC in the 70–90 GeV mass range consistent with the PAMELA, HESS, and Fermi/LAT astrophysical data as shown in Ref. [8]. The lack of triple couplings to gauge bosons delay the restoration of unitarity which effectively occurs only when the heavy KK gauge bosons associated to the larger gauge group start to propagate [13] resulting in an enhanced cross section compared to the SM case as we will see in section I. As in the case of the single Higgs production [9], the two far forward tagging jets serve as triggers and as an efficient tool to reduce the SM backgrounds. We show that with sufficient integrated luminosity the Higgs dark matter particle of this model can be observed at the CERN LHC.

## B. The Effective Lagrangian of the $SO(5) \otimes U(1)$ Gauge-Higgs Unification Model

The model we are considering is a gauge theory based on the group  $SO(5) \otimes U(1)$  with an warped extra dimension [4]. The 4D Higgs boson is identified with a part of the extra-dimensional component of the gauge bosons and the Higgs couplings to all particles are fixed by the gauge principle. The 4D neutral Higgs boson corresponds to quantum fluctuations of the Aharonov-Bohm phase  $\theta_H$  in the extra dimension.

The one-loop generated effective Higgs potential  $V_{eff}(\theta_H)$  depends on the Aharonov-Bohm phase  $\theta_H$  along the fifth dimension. It has been shown that the effective potential has a global minimum at  $\theta_H = \pm\pi/2$  [4] and small fluctuations around the minimum  $\hat{\theta}_H = \pi/2 + H(x)/v$  introduce the Higgs field  $H$  responsible for the electroweak symmetry breaking. The effective Higgs potential must be invariant under  $H \rightarrow -H$ . The Higgs field is odd under the  $H$ -parity transformations while all other SM particles are even.

For our studies the relevant effective four dimensional interaction Lagrangian of the  $SO(5) \otimes U(1)$  gauge theory in 5D warped spacetime is given by

$$\begin{aligned} \mathcal{L}_{eff} = & \frac{g^2 v}{2} \cos(\theta_H) W_\mu W^\mu H + \frac{g^2 v}{8c_W^2} \cos(\theta_H) Z_\mu Z^\mu H \\ & + \frac{g^2}{4} \cos(2\theta_H) W_\mu W^\mu HH + \frac{g^2}{8c_W^2} \cos(2\theta_H) Z_\mu Z^\mu HH \\ & + \sum_f \frac{m_f}{2v^2} \cos(2\theta_H) \bar{\psi}_f \psi_f HH \end{aligned} \quad (2)$$

As a consequence of the conservation of the  $H$ -parity all triple vertices involving Higgs interactions vanish at  $\theta_H = \pi/2$  as can be seen from the Lagrangian right above. Only quartic interactions with SM strength survive and the Higgs boson becomes absolutely stable.

Note that the vanishing of  $ZZH$  coupling evades the LEP bound on the Higgs mass. As a matter of fact, all possible collider constraints on the Higgs mass are evaded. Nonetheless, mass bounds from WMAP, PAMELA, HESS, and Fermi/LAT allow a narrow 70 – 90 GeV [8] window for collider searches.

The lack of triple couplings causes the violation of tree-level unitarity at  $\mathcal{O}(1)$  TeV. The scattering amplitudes take the largest values precisely for  $\theta_H = \pi/2$  in warped space-times in these classes of models as shown in Ref. [13]. The  $\mathcal{O}(E^2)$  terms which cause the unitarity violation are cancelled as soon as the heavier KK-modes of gauge bosons start to propagate leading to a constant behavior of the amplitudes as a function of the energy  $E$  at a scale around  $\mathcal{O}(10)$  TeV [13] if the KK mass scale is  $m_{KK} \gtrsim 1$  TeV. That is the reason why we expect the double Higgs dark matter production has a much larger cross section in the weak boson fusion channel as compared to the SM case at  $\mathcal{O}(1)$  TeV scale. The WBF process is intimately related to the EWSB and the violation or the delay in the restoration of tree-level unitary of the  $WW \rightarrow WW$  scattering is a sign that new physics must come into play [14].

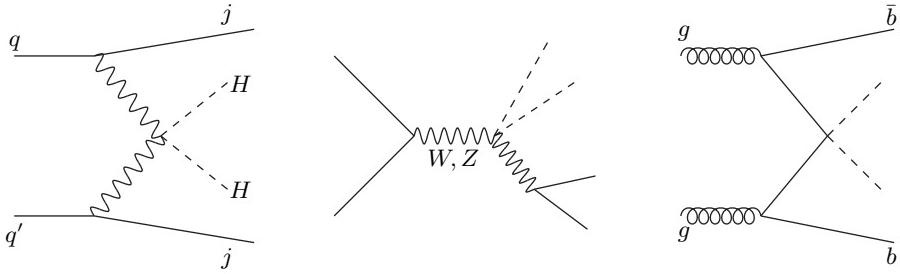


Figure 1: Feynman diagrams contributing to the  $pp \rightarrow jjHH$  process. From left to right we show the WBF, double Higgsstrahlung, and the gluon fusion QCD contribution respectively. There are additional QCD diagrams not shown in the figure initiated by  $q\bar{q}$ ,  $gb(\bar{b})$ , and  $b\bar{b}$ .

### C. Search strategy at the CERN LHC

The two far forward hard jets plus missing energy topology has already been studied in the literature for a single invisibly decaying Higgs boson production in weak boson fusion [9]. The backgrounds are exactly the same and the whole analysis can be done along the same lines. For this reason we use the results and discussions for the backgrounds analysis from that work and simulate only the signal events for  $pp \rightarrow jjHH \rightarrow jjE_T$ .

The backgrounds consist of process leading to two jets and missing transverse momentum: (1) QCD and WBF  $Zjj \rightarrow jj\nu\bar{\nu}$ , (2) QCD and WBF  $Wjj \rightarrow jjl\nu$  where the charged lepton is not identified, (3) QCD multijet production with large missing momentum generated by energy mismeasurements or high transverse momentum particles escaping detection through the beam-hole.

Our signal was simulated at parton level with full tree level matrix elements and full CKM matrix using the CalcHEP package [16] including electroweak and QCD contributions. The electroweak contributions consist of genuine WBF diagrams and double Higgsstrahlung diagrams with a  $Z$  or  $W$  boson decaying into jets as can be seen at Figure (1). The QCD contributions are initiated by gluons, light or bottom partons and the Higgses are radiated off the final state bottom quarks.

We do not take into account the contributions from the heavy KK-modes of gauge bosons since we expect they will unitarize the scattering amplitudes only at a some higher scale as discussed in section B. At the  $\mathcal{O}(1)$  TeV scale relevant for the LHC phenomenology the WBF cross section is expected to increase with the energy in this model.

In order to be consistent with the simulations performed in Ref. [9] from where we took the results for backgrounds we employed CTEQ4L parton distribution functions [15] at the factorization scale  $\mu_F = \min(p_T)$  of the defined jets. The electroweak parameters  $\sin^2 \theta_W = 0.23124$ ,  $\alpha_{em} = 1/128.93$ ,  $m_Z = 91.189$  GeV, and  $m_W = 79.95$  GeV were taken from Ref. [9] as well. We simulate experimental resolutions by smearing the energies (but not directions) of the defined jets with a Gaussian error given by  $\Delta E/E = 0.5/\sqrt{E} \oplus 0.02$  ( $E$  in GeV).

We checked that all kinematic distributions used to impose cuts on the final states jets and missing momentum in our case are very similar to those of  $pp \rightarrow jjH$  of Ref. [9]. Therefore, we can assume the same strategy to suppress the backgrounds and impose the same cuts

$$\begin{aligned}
 p_{T,j} &> 40 \text{ GeV} & |\eta_j| &< 5.0 \\
 |\eta_{j_1} - \eta_{j_2}| &> 4.4 & \eta_{j_1} \cdot \eta_{j_2} &< 0 \\
 \not{p}_T &> 100 \text{ GeV} & m_{jj} &> 1200 \text{ GeV}
 \end{aligned} \tag{3}$$

The cuts on the transverse momentum and rapidity of the defined jets are the standard WBF selection cuts while the missing momentum cut explores the features of our signal with two final state dark matter particles. A very large cut on the invariant mass of the two tagging jets,  $m_{jj}$ , helps to reduce the backgrounds further.

The jets from the double Higgsstrahlung contributions (see Fig. (1)) are on the  $W$  or  $Z$  mass shell being eliminated after the jets invariant mass cut is applied remaining only the genuine WBF contributions. The QCD contributions:  $gg(q\bar{q}) \rightarrow b\bar{b}HH$ ,  $b\bar{b} \rightarrow ggHH$ ,  $gb(\bar{b}) \rightarrow gb(\bar{b})HH$  involve double Higgs radiation from the bottom quark lines which

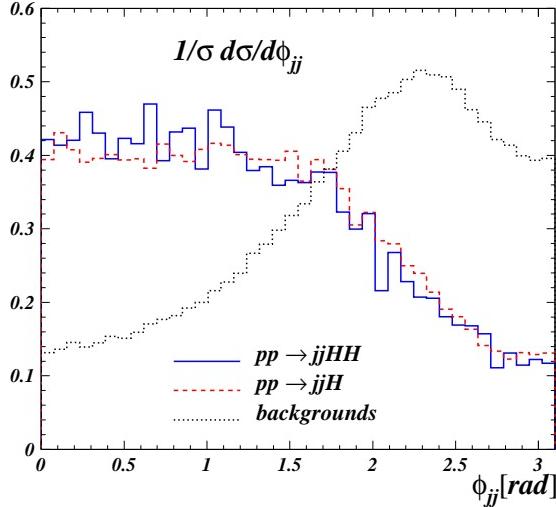


Figure 2: The normalized distributions of the azimuthal angle separation between the tagging jets for the double Higgs ( $pp \rightarrow jjHH$ ), single Higgs ( $pp \rightarrow jjH$ ), and total background after applying the cuts (3).

are suppressed by  $m_b/2v^2$  (see Eq. (2)). Moreover, the jets from this class of contributions are typically central and softer than the jets from WBF contributions being negligible after imposing the cuts. The large SM QCD backgrounds are strongly reduced after the missing momentum cut is applied. A survival probability associated to a central soft jet activity veto of 0.28 for QCD processes, as estimated in [17] and used in Ref. [9], is crucial to reduce these backgrounds and enhance the signal to background ratio. Yet they are ineffective against the SM WBF processes whose survival probability is high: 0.82.

For this reason the dominant background contribution after the cuts (3) is the Standard Model WBF contribution. To suppress this background the following cut on the azimuthal angle between the tagging jets,  $\phi_{jj}$ , was proposed in Ref. [9]

$$\phi_{jj} < 1 \quad (4)$$

It explores the nature of the particle being produced between the tagging jets: a scalar (Higgs) for the signal and a vector ( $W, Z$  boson) for the background. The spin of this particle determines the angular distributions of the tagging jets and eventually of the products of their decays.

We show in Figure (2) the normalized distributions for the  $\phi_{jj}$  variable for our double Higgs signal, the single invisibly decaying Higgs, and the total background after applying the cuts from Eq. (3). The effect of the spin nature of the particles being produced is evident from this plot and motivates the cut (4) devised to suppress the SM weak boson fusion background.

Despite the fact the shape of the Higgs signals are very similar, the cut proposed in Ref. [9] to clean up the Standard Model WBF background is not too effective in our case from the point of view of the required integrated luminosity to observe a  $5\sigma$  signal as compared to the single Higgs case as we discuss in the next section. As suggested in Ref. [9], an analysis based on the shape of the  $\phi_{jj}$  distribution could be a good idea to separate signal from backgrounds but the reduced signal cross section after cuts in our case is a challenge for that purpose.

## I. RESULTS AND DISCUSSIONS

The signal total cross section without cuts is 30.1(28.3) fb for a 70(90) GeV Higgs boson at the 14 TeV LHC while the total background cross section amounts to 2.79 pb. As we anticipated in section B the  $pp \rightarrow jjHH$  rate in this gauge-Higgs unification model is about 5 times larger than its SM analog whose WBF production cross section for a 70 GeV Higgs mass is 6.3 fb. The same set of parameters, factorization scale and parton distribution functions for the Higgs dark matter case were used in this computation.

After applying all the basic cuts (3) and the  $\phi_{jj}$  cut, and assuming the same survival probability for a central soft jet veto of  $P_{surv} = 0.87$  for our signal as in Ref. [9], we found 4.20(4.18) fb for the signal against 167 fb for the total background for a 70(90) GeV Higgs boson mass. Based on these rates a  $5\sigma$  significance observation is possible

$\sigma(\text{fb})$	signal: $m_H = 70(90)$ GeV	Total Background	$\mathcal{L} (\text{fb}^{-1})$
basic cuts (bc)	10.0(9.6)	918	229(249)
$\text{bc} + \phi_{jj} < 1$	4.20(4.18)	167	237(239)

Table I: Signal and background cross sections after basic cuts (3) and basic cuts plus the  $\phi_{jj}$  cut of Eq. (4). The survival probability after a soft central jet veto is incorporated already as discussed in section C. We show the results for a 70 and a 90 GeV Higgs boson. The last column displays the required integrated luminosity for a  $5\sigma$  significance observation.

with  $237(239)\text{fb}^{-1}$  of integrated luminosity for a 70(90) GeV Higgs dark matter particle. The table I summarizes our results.

The impact of the  $\phi_{jj}$  cut (4) on the double Higgs production is fairly the same as the single Higgs process representing a dilution factor of 0.37 in our case and 0.40 in the single Higgs case. The backgrounds on their turn are suppressed by a factor of 0.18 which motivates the cut in the single Higgs case after all. The impact of this cut on the required luminosity is mild though increasing from  $229(249) \text{ fb}^{-1}$  to  $237(239) \text{ fb}^{-1}$  the required integrated luminosity for a  $5\sigma$  observation of a 70(90) GeV Higgs.

It indicates that there is still some room for an optimum choice of cuts for example tightening the missing  $p_T$  or the jets invariant mass cut. On the other hand a complete simulation taking into account hadronization, pile-up effects and more realistic detector efficiencies is necessary in order to evaluate the LHC potential more precisely.

An interesting question arisen looking at the  $\phi_{jj}$  distribution of Figure (2) is how to discriminate between a Higgs dark matter of the classes of models under consideration and a single Higgs decaying to an invisible final state with a large branching ratio as considered in Ref. [9]. It is evident it cannot be done based on the kinematic distributions of the jets. Observing signals associated to a single invisible Higgs boson production in other channels would be important for that task once we do not expect seeing signals for the classes of models we considering here based on our results and on the results from Ref. [7] as well.

Another possibility is to find a way to measure the growth in the total cross section as a function of the center-of-mass energy of the collision. The weak boson fusion is the best suited process to that goal, however it cannot be done easily at hadron colliders without relying on the decay products of the Higgs boson [14]. A future linear collider could do that job in the WBF channel once the energy of the incoming leptons can be tuned.

It's worth mentioning that dark matter production in weak boson fusion is not likely to occur at hadron colliders in the framework of models presenting CDM candidates like the MSSM or UED for example. In the MSSM case it has been shown [18] that destructive interference between WBF-type diagrams and bremsstrahlung diagrams contributing to the lightest neutralino production decreases the rates to an attobarn level for  $pp \rightarrow jj\tilde{\chi}^0\tilde{\chi}^0$  at the LHC. On the other hand in the UED models the lightest KK particle is an almost pure  $U(1)_Y$  gauge boson which strongly suppresses the couplings to other gauge bosons and probably depletes the WBF channel as well.

## II. CONCLUSIONS

In the  $SO(5) \otimes U(1)$  gauge-Higgs unification model in the Randall-Sundrum spacetime proposed in Ref. [4] the 4D Higgs field becomes a part of the fifth-dimensional component of the gauge fields. Electroweak symmetry is broken dynamically through loop corrections to the Higgs potential and the conservation of an additional quantum number called *H-parity* renders absolute stability to the Higgs boson which becomes a natural cold dark matter candidate. As a consequence of vanishing of all triple couplings to the Standard Model spectrum by virtue of *H-parity* conservation, the Higgs boson can only be produced in pairs through quartic couplings to massive gauge bosons and fermions. The mass of such a Higgs dark matter is constrained from recent astrophysical data to lie in the 70-90 GeV mass range.

In this paper we show that the 14 TeV LHC has the potential to discover such a Higgs dark matter particle of 70(90) GeV mass with  $237(239) \text{ fb}^{-1}$  of integrated luminosity for a  $5\sigma$  observation in the weak boson fusion channel following the same search strategy used in the single invisibly decaying Higgs case of Ref. [9]. On the other hand, the cut on the azimuthal angle between the tagging jets were found to be less effective from the point of view of reducing the amount of data necessary for discovery compared to the single Higgs case which demonstrates that there is still room for optimization of the search strategy.

As a final comment, the enhanced production cross section compared to the SM case is due the lack of cancellations between the triple and quartic contributions. This feature may help to establish the model if the growth in the production cross section as a function of the center-of-mass energy could be determined for example in a future linear collider or using dedicated methods to that aim as for example was proposed in [14].

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